Sborník vědeckých prací Vysoké školy báňské - Technické univerzity Ostrava

číslo 2, rok 2012, ročník XII, řada stavební

článek č. 6

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DETERMINATION OF THE BLAST INDUCED LOAD

STANOVENÍ ZATÍŽENÍ VYVOLANÉHO VÝBUCHEM

Abstract

Blast load on building structures can be determined by several simple calculation methods. Some of them are verified in this paper. For determination of overpressure, various computational methods exist but their utilization in practice is not clear. The contribution presents the results of evaluation of 12 equations, pointing out the most suitable formula for given geometry and type of gas.

Keywords

Explosion, venting, blast load, empirical calculation.

Abstrakt

V příspěvku jsou ověřovány jednoduché výpočetní přístupy vedoucí ke stanovení výbuchového zatížení na stavební konstrukce. Pro stanovení přetlaku při výbuchu plynu existují různé výpočetní metody, ale není zcela ověřeno, do jaké míry jsou využitelné v praxi. Článek představuje výsledky vyhodnocení 12 rovnic a poukazuje na nejvhodnější vzorec pro danou geometrii a typ plynu.

Klíčová slova

Výbuch, odlehčení výbuchu, výbuchové zatížení, empirický výpočet.

1 INTRODUCTION

Explosion venting belongs to the group of construction arrangements for explosion protection. This arrangement by itself could not prevent the explosion but instead danger effects are limited to reasonable size. If it is not possible to avoid the creation of explosive atmosphere and to eliminate explosion hazard with the help of active explosion prevention (or if these precautions are not suitable), then the objects should be designed in such a way that explosion effects are lowered to the safety margin. The arrangements ensure that damage of structure and exposure of people would be minimised.

In practice, most internal explosions are solved as venting explosions. At pressure increase in the object or room, so-called vent areas (e. g. windows, doors, partition walls etc.) are relieved at

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certain value. In the case the explosion is vented, final generated pressure is much lower. Many authors have been focused on the determination of this reduced pressure and lots of calculation formulas have been published. Chosen formulas are presented in this contribution.

2 TERMS AND DEFINITIONS

Table 1 shows used terms and definition. It also specifics single variables and constants used further in this text.

Tab.1: Used terms and definitions

Term	Definition
p_{red}	Reduced pressure
π_{red}	Dimensionless reduced pressure
p_{stat}	Static activation pressure
p_0	Initial pressure
A_s	Internal area of enclosure
A_v	Vent area
V	Volume of enclosure
E_0	Expansion ratio
c_0	Sound speed
χ	Turbulence factor
π_v	Dimensionless air-release parameter
π_0	Ludolf number
γ_b	Adiabatic coefficient of combustion
γ_u	Adiabatic compression coefficient
S_{u0}	Normal burning velocity
S_0	Laminar burning velocity
W	Weight of m^2 of vent area
S_{fl}	Burning of flame velocity
C_d	Coefficient of discharge (resistance)
K	Ventilation coefficient
A_{min}	Minimal size of envelope areas
A_{max}	Maximum size of envelope areas
d, f, g, h	Constants
$\overline{S}_0$	Dimensionless parameter
$\overline{A}$	Dimensionless parameter
Br, Br_t	Bradley number
χ/μ	Number expressing relation between deflagration and turbulent flow
D	Diameter
C	Coefficient
A_{sv}	Area of surface with vent area

3 EQUATIONS USED FOR OVERPRESSURES CALCULATION

This chapter describes particular computational procedures for calculation of reduced explosion pressure, or more precisely blast load of the structure, by various sources and authors. For particular procedures, important notes or limitations that should be followed to obtain correct results are introduced.

According to ČSN EN 1991-1-7 [5]

$$p_{red} = 3 + p_{stat} \tag{1}$$

or

$$p_{red} = 3 + \frac{p_{stat}}{2} + \frac{0{,}04}{\left(\frac{A_v}{V}\right)^2} \tag{2}$$

Note:
Pressure p_{red} and p_{stat} is considered in units of kPa; V and A are in m^3 and m^2. Pressure p_{red} with higher value is always taken into account.

Limitation:
Valid only for $V < 1000\ m^3$, A_v/V ranges from 0,05 to 0,15 m^{-1}.

According to NFPA 68 [9]

$$p_{red} = (C \cdot A_S)^2 \cdot A_V^{-2} \tag{3}$$

Note:
Pressure p_{red} is counted in units of bar g, coefficient C in $bar^{1/2}$. A_s and A_v are in m^2.

Limitation:
Valid only for $p_{stat} < 0{,}1$ bar g.

According to Runess [12]

$$p_{red} = 1{,}804 \cdot 10^{-4} \cdot \left[D^2 \cdot S_{fl} \cdot (E_0 - 1)\right]^2 \cdot A_V^{-2} \tag{4}$$

Note:
Pressure p_{red} is expressed in units of bar g, D and A_v are in m and m^2, burning of flame velocity S_{fl} in m/s, E_0 is a constant.

According to Simpson [13, 2]

$$p_{red} = \left[\frac{1}{d \cdot V^f \cdot e^{(g \cdot p_{stat})}}\right]^{1/h} \cdot A_V^{1/h} \tag{5}$$

Note:
Pressure p_{red} is expressed in units of bar g, V and A_v are in m^3 and m^2, d, f, g, h are dimensionless constants.

Limitation:
$0{,}1 < p_{stat} < 0{,}5$; $p_{stat} + 0{,}1 < p_{red} < 2$; $1 < V < 5000$.

According to Bradley (formula No. 1) [3]

$$p_{red} = 2{,}43 \cdot \left(\frac{\overline{A}}{\overline{S_0}}\right)^{-0{,}6993} \qquad for \quad p_{red} > 1\,bar\ g \tag{6}$$

$$p_{red} = 12{,}46 \cdot \left(\frac{\overline{A}}{\overline{S_0}}\right)^{-2} \qquad for \quad p_{red} < 1\,bar\ g \tag{7}$$

Calculation of parameters $\overline{A}$ and $\overline{S_0}$:

$$\overline{A} = \frac{C_d \cdot A_V}{A_S} \tag{8}$$

$$\overline{S_0} = \frac{S_{u0}}{c_0} \cdot (E_0 - 1) \tag{9}$$

Note:
Pressure p_{red} is expressed in units of bar g, A_s and A_v are in m^2, S_{u0} and c_0 in m/s, $\overline{A}$ is dimensionless vent area, $\overline{S_0}$ is dimensionless venting parameter and C_d is dimensionless constant.

Limitation:
Maximum reduced pressure does not exceed venting opening pressure.

According to Bradley (formula No. 2) [3]

$$p_{red} = 4{,}82 \cdot p_{stat}^{0{,}375} \cdot \left(\frac{\overline{A}}{\overline{S_0}}\right)^{-1} \tag{10}$$

For calculation of $\overline{A}$ and $\overline{S_0}$ see Bradley (formula No. 1).

Note:
Pressure p_{red} and p_{stat} is considered in units of bar g.

According to Cubbage and Simmonds (formula No. 1) [4, 3, 1]

$$p_{red} = 0{,}365 \cdot \left(\frac{\overline{A}}{\overline{S_0}}\right)^{-1} \tag{11}$$

For calculation of $\overline{A}$ and $\overline{S_0}$ see Bradley (formula No. 1).

Note:
Pressure p_{red} is expressed in units of bar g.

According to Rasbash [10]

$$p_{red} = 0{,}15 \cdot p_{stat} \cdot 0{,}365 \cdot \left(\frac{\overline{A}}{\overline{S_0}}\right)^{-1} \tag{12}$$

For calculation of $\overline{A}$ and $\overline{S_0}$ see Bradley (formula No. 1).

Note:
Pressure p_{red} and p_{stat} is considered in units of bar g.

Limitation:
$0{,}2 < A_v/A_{sv} < 1$, $p_{stat} < 0{,}48$ bar g.

According to Yao [14]

$$p_{red} = \left[\frac{0{,}375 \cdot \chi^{0{,}675} \cdot E_0^{7/6}}{E_0 - 1}\right]^2 \cdot \left(\frac{\overline{A}}{\overline{S_0}}\right)^{-2} \tag{13}$$

For calculation of $\overline{A}$ and $\overline{S}_0$ see Bradley (formula No. 1).

Note:
Pressure p_{red} is expressed in units of bar g, χ and E_0 are dimensionless constants.

According to Molkov (formula No. 1) [7]

$$\pi_{red} = \frac{p_{red} - p_0}{p_0} = 9{,}8 \cdot \left[\frac{B_r \cdot (E_0 - 1)}{(36 \cdot \pi_0)^{1/3} \cdot \sqrt{\gamma_u}} \cdot \frac{\mu}{\chi}\right]^{-2{,}4} \tag{14}$$

Calculation of parameter Br (Bradley number):

$$Br = \frac{A_V}{V^{2/3}} \cdot \frac{C_0}{S_{u0} \cdot \left(E_0 - \frac{1 - \frac{1}{\gamma_b}}{1 - \frac{1}{\gamma_u}}\right)} \tag{15}$$

Calculation of parameter χ/μ:

$$\frac{\chi}{\mu} = 0{,}9 \cdot \left[\frac{\left(1 + 10 \cdot V^{1/3}\right) \cdot (1 + 0{,}5 \cdot Br)}{1 + \pi_v}\right]^{0{,}37} \tag{16}$$

Calculation of parameter π_v:

$$\pi_v = \frac{p_{stat}}{p_0} \tag{17}$$

Note:
Pressures π_{red}, p_{red}, p_{stat} and p_0 are expressed in units of bar g. V and A_v are in m^3 and m^2, S_{u0} and c_0 are calculated in m/s, E_0, γ_u, γ_b are dimensionless constants.

According to Molkov (formula No. 2) [6]

$$\pi_{red} = Br_t^{-2{,}4} \quad for \quad \pi_{red} < 1 \tag{18}$$

$$\pi_{red} = 7 - 6 \cdot Br_t^{0{,}5} \quad for \quad \pi_{red} > 1 \tag{19}$$

Calculation of parameter Br_t:

$$Br_t = \frac{\sqrt{\frac{E_0}{\gamma_{u0}}}}{\sqrt[3]{36 \cdot \pi_0}} \cdot Br \cdot \frac{\mu}{\chi} \tag{20}$$

For calculation of Br, χ/μ and π_v see Molkov (formula No. 1).

Note:
Pressures p_{red} and p_{stat} are expressed in units of bar g. V and A_v are in metric units m^3 and m^2, S_{u0} and c_0 are calculated in m/s, E_0, γ_u, γ_b are dimensionless constants.

According to Cubbage and Simmonds (formula No. 2) [4]

$$P_1 = S_0 \cdot \frac{(4{,}3 \cdot K \cdot W + 28)}{V^{\frac{1}{3}}} \tag{21}$$

$$P_2 = 58 \cdot S_0 \cdot K \tag{22}$$

Calculation of parameter K:

$$K = \frac{A_S}{A_V} \tag{23}$$

Note:
P_1 is reaction pressure of vent areas and P_2 is maximum explosion pressure in given space. Both pressures are expressed in mbar g. V, A_s and A_v are in m^3 and m^2, W is counted in kg/m^2 and S_{u0} in m/s.

Limitations:
Coefficient $K < 5$; weight of vent area per unit area does not exceed 24 kg.m^{-2}; no support is used to keep a venting element in its position; ratio of maximum and minimum size of envelope areas is smaller than 3:1.

4 INPUT DATA AND COMPUTATIONAL ASSUMPTIONS

The measurements were executed at stoichiometric concentration of homogeneous methane-air mixture in cubic equipment with volume of 0,250 m^3. Table 2 introduces the constants used for calculations of reduced pressures.

Tab.2: The constants used for calculations of reduced pressures [11]

Gas mixture	S_{u0} (m/s)	C_d (m/s)	c_0 (m/s)	E_0 (-)	γ_u (-)	γ_b (-)
Methane 9,5 %	0,44	0,6	353	7,48	1,38	1,18

Testing equipment was built as a reduced physical model of the object. In the envelope of the model, vent opening was installed in the middle of one side. Area of square-shaped opening was 0,040 m^2 and the diaphragm with average value of static activation pressure of 0,226 bar was used as a filling of the opening. Area of internal surface of the model was 2,418 m^2, area of one side with the opening was 0,393 m^2, weight of 1 m^2 of vent area was 0,092 kg, minimum size of envelope areas was 0,605 m and maximum size of envelope areas was 0,650 m. In the experiment enclosure, any obstructers for increase of the turbulence did not occur. Ignition of the mixture was supposed to be in the centre of the model [8].

For particular formulas, various input data are used. Table 3 illustrates particular variables and constants entering the calculation in their relationship to single computational approaches.

Tab.3: Use of variables and constants for calculation of particular formulas

Author, source of formula	Variables and constants									
	p_{stat}	P_0	V	A_V	A_s	D	E_0	S_{u0}	S_{fl}	C
	C_d	c_0	χ	γ_u	γ_b	W	A_{sv}	A_{min}	A_{max}	S_0
ČSN EN 1991-1-7	✓	-	✓	✓	-	-	-	-	-	-
	-	-	-	-	-	-	-	-	-	-
NFPA68	✓	-	-	✓	✓	-	-	-	-	✓
	-	-	-	-	-	-	-	-	-	-
Simpson	✓	-	✓	✓	-	-	-	-	-	-
	-	-	-	-	-	-	-	-	-	-
Runes	-	-	✓	✓	-	✓	-	-	✓	-
	-	-	-	-	-	-	-	-	-	-
Bradley 1	-	-	-	✓	✓	-	✓	✓	-	-
	✓	✓	-	-	-	-	-	-	-	-
Bradley 2	-	-	-	✓	✓	-	✓	✓	-	-
	✓	✓	-	-	-	-	-	-	-	-
Cubbage and Simmonds 1	✓	-	-	✓	✓	-	✓	✓	-	-
	✓	✓	-	-	-	-	-	-	-	-
Rasbash	✓	-	-	✓	✓	-	✓	✓	-	-
	✓	✓	-	-	-	-	✓	-	-	-
Yao	-	-	-	✓	✓	-	✓	✓	-	-
	✓	✓	✓	-	-	-	-	-	-	-
Molkov 1	✓	✓	✓	✓	-	-	✓	✓	-	-
	-	✓	-	✓	✓	-	-	-	-	-
Molkov 2	✓	✓	✓	✓	-	-	✓	✓	-	-
	-	✓	-	✓	✓	-	-	-	-	-
Cubbage and Simmonds 2	-	-	✓	✓	-	-	-	-	-	-
	-	-	-	-	-	✓	✓	✓	✓	✓

✓ given variable or constant has to be entered for calculation of the formula

- it is not need to enter given variable or constant for calculation of the formula

5 CALCULATED RESULTS

Only eight of presented twelve equations could be used for given conditions. Remaining equations did not satisfy mentioned limitations of particular formulas. Calculated values are shown in table 4.

Tab.4: Calculated values of reduced pressures

Formula	Runes	Bradley 1	Bradley 2	Cubbage and Simmonds 1
Reduced pressure (bar)	0,715	2,104	2,133	0,297
Formula	Rasbash	Yao	Molkov 1	Molkov 2
Reduced pressure (bar)	0,331	1,577	0,410	0,332

Figure 1 demonstrates graphic view of single values of reduced pressures according to different computational approaches.

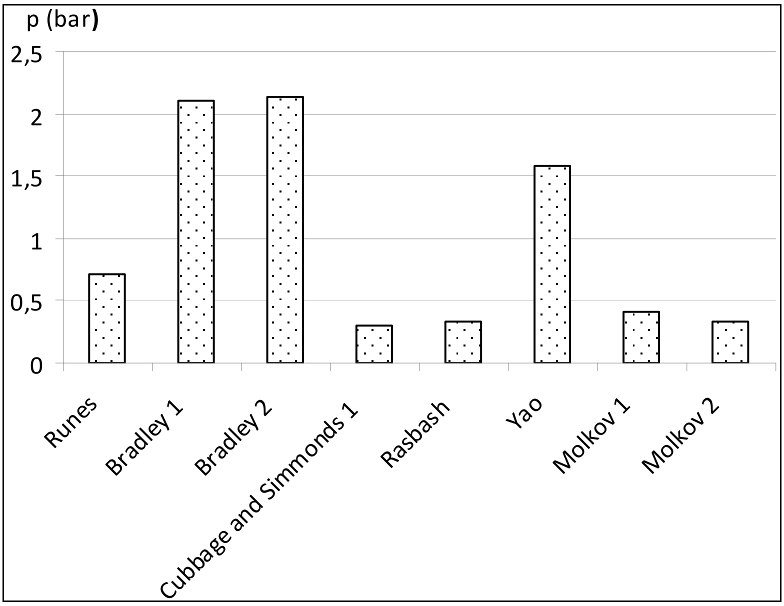

Fig.1: Values of calculated reduced pressures

Experiments were executed on testing equipment at atmospheric pressure of 0,995 bar and internal temperature of 12 °C. For each of the concentration of methane-air mixture in the range of explosion limits LEL (lower explosion limit) and UEL (upper explosion limit), four experiments were realized. At stoichiometric concentration of the mixture, average value of reduced explosion pressure was 1,046 bar. This value was compared to values calculated according to formulas mentioned above.

Value of relative deviation δ between calculated and measured reduced pressures was determined as follows:

$$\delta = 100 \cdot \frac{\left(p_{calc} - p_{exp}\right)}{p_{exp}} \tag{24}$$

Figure 2 illustrates values of relative deviations of calculated and measured reduced pressures.

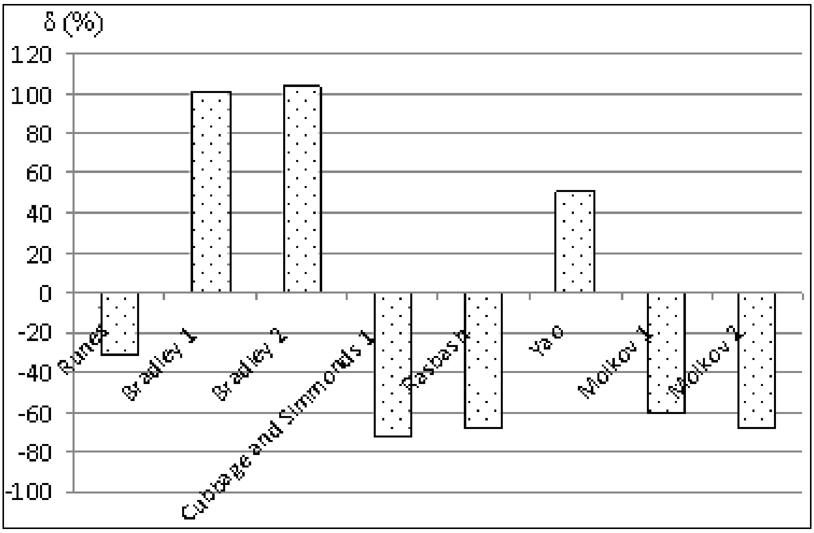

Fig.2: Values of relative deviations of calculated and measured reduced pressures

6 CONCLUSIONS

This contribution introduces calculation of reduced explosion pressure according to several methods and following comparison of calculated and experimentally found values. Result of comparison shows that calculation of reduced pressures according to the formulas is rather approximate. In the case of the second formula according to Bradley, deviation from experimentally measured value was almost 104 %. The most precise result was determined according to Runes. Calculated value differed from measured value by less than 32 %. Unfortunately, reduced pressure can not be calculated according to the formula presented in valid standard ČSN EN 1991-1-7. Parameters of testing equipment do not conform the limitation about ratio of Av/V in the range between 0,05 to 0,15 m^{-1}.

It should be pointed that results of formula used in this paper can differ significantly. Venting explosion pressure depends on many factors that's why it could not be uniquely determined which of the formulas is the most precise. It can only be assessed which formula is the most precise for concrete model, on the basis of used combustible mixture, volume and geometry of equipment and size, shape, way and conditions of venting.

ACKNOWLEDGEMENT

This work was supported by the project of the Ministry of the Interior of the Czech Republic No. VG2VS/036 – "Improvised sheltering, warning, and information of population in the buildings for gathering large numbers of persons".

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